

Higgs Boson Searches at LEP

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The results of the Higgs boson searches performed by the four LEP experiments at centre-of-mass energies between 189 GeV and 209 GeV corresponding to an integrated luminosity of 2461 pb^{-1} are presented here. Searches have been performed for Higgs in the Standard Model (SM), in 2 Higgs Doublet Models (2HDM's), for doubly charged, fermiophobic and invisible Higgs as well as a decay mode independent search. Most of the results of the four experiments have been combined by the LEP Higgs working group.

1 Introduction

We present combined results from the ALEPH, DELPHI, L3 and OPAL Collaborations on searches for the SM Higgs boson, for the neutral Higgs bosons h^0 and A^0 in the Minimal Supersymmetric Standard Model (MSSM), for charged Higgs bosons, for “fermiophobic” Higgs decaying into a pair of photons. Individual experiments have prepared analyses for future combinations: searches for neutral Higgs bosons h^0 and A^0 in different types of 2HDM's, for charged Higgs decaying into $A^0, W^{\pm*}$, for doubly charged Higgs as well as a decay mode independent search are presented. The analyses are based on 2461 pb^{-1} of e^+e^- collisions at LEP2, for centre-of-mass energies between 189 and 209 GeV. Each experiment has generated Monte Carlo event samples for the Higgs signal and the various background processes, typically, at 189, 192, 196, 200, 202, 204, 206, 208 and 210 GeV energies. Cross-sections, branching ratios, distributions of the reconstructed mass and other discriminating variables relevant to the combination have been interpolated to energies which correspond to the data sets. In this procedure special care has been taken to the regions of kinematic cutoff where the signal and background distributions vary rapidly. It has been established that the interpolation procedures do not add significantly to the final systematic errors.

The main sources of systematic error affecting the signal and background rate predictions are included taking into account correlations between search channels, LEP energies and individual

experiments. This is done using an extension of the method of Cousins and Highland¹ where the confidence levels are the averages of a large ensemble of Monte Carlo experiments, each one with a different choice of signal and background, varied within the errors.

2 Search for the SM Higgs boson

At LEP the SM Higgs boson is expected to be produced mainly via the *Higgs-strahlung* process $e^+e^- \rightarrow H^0 Z^0$, while contributions from the $WW \rightarrow H$ fusion channel, $e^+e^- \rightarrow H^0 \nu_e \bar{\nu}_e$, are typically below 10%. The searches performed by the four LEP collaborations encompass the usual $H^0 Z^0$ final state topologies, commonly called ‘four-jet’ ($H^0 Z^0 \rightarrow b\bar{b}q\bar{q}$), ‘missing energy’ ($b\bar{b}\nu^+\nu^-$), ‘leptonic’ ($b\bar{b}e^+e^-$ and $b\bar{b}\mu^+\mu^-$) and ‘tau’ channels ($b\bar{b}\tau^+\tau^-$ and $\tau^+\tau^-q\bar{q}$). The searches in the missing energy channel are optimised for *Higgs-strahlung*, but are also sensitive to the $WW \rightarrow H$ fusion process. The analyses are based on 2461 pb^{-1} of data taken at centre of mass energies $189 \leq \sqrt{s} \leq 209 \text{ GeV}$. The results of the final combination of the LEP results on SM Higgs searches is presented here, more details can be found in². The combined LEP data are used to test two hypotheses: the *background-only* (“*b*”) hypothesis, which assumes no Higgs boson to be present in the mass range investigated, and the *signal + background* (“*s + b*”) hypothesis, where Higgs bosons are assumed to be produced according to the model under consideration. A global *test-statistic* Q^2 is constructed which allows the experimental result Q_{observed} to be classified between the *b*-like and *s + b*-like situations. The probability density functions of $Q(m_H)$ are integrated from the observed value to plus or minus infinity to form the confidence levels CL_{s+b} and CL_b , which express the probabilities that the outcome of an experiment is more *s + b*-like or less *b*-like, respectively, than the outcome represented by the set of selected events. To prevent to extend the limit beyond the range of sensitivity the ratio $CL_s = CL_{s+b}/CL_b$ is used to set mass exclusion limits.

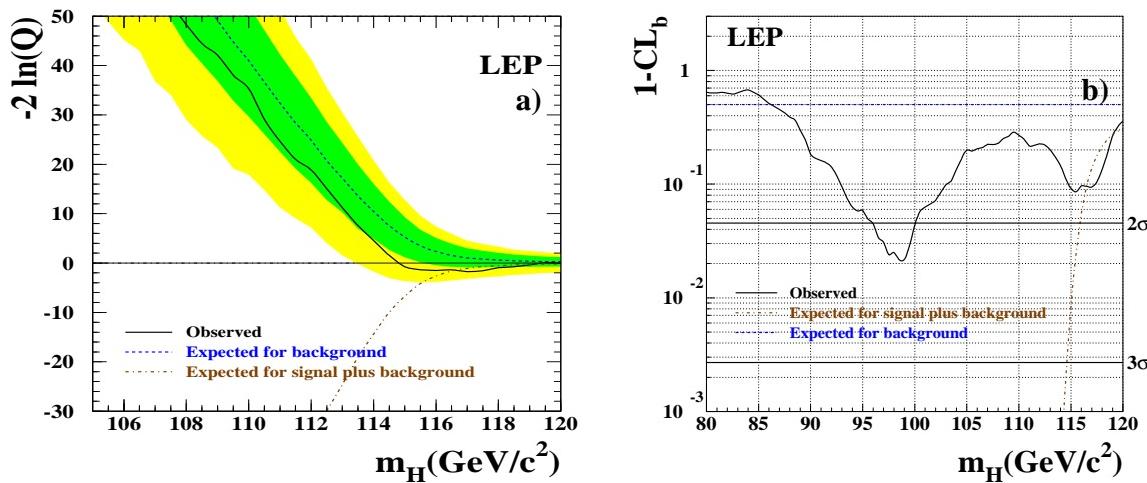


Figure 1: a) The test-statistic as a function of m_H . Dashed line: expectation and 1σ and 2σ probability bands around it in the background only hypothesis; solid curve: observed results; dotted line: median result expected in presence of signal where $m_H=115 \text{ GeV}/c^2$. b) $1 - CL_b$ as a function of m_H . Straight line at 50%: median result in the absence of a signal. Solid curve: observed result. Dashed curve: median result expected for a signal when tested at the “true” mass.

Figure 1.a shows the test-statistic $-2\ln Q$ versus the test mass m_H for the combined LEP data: there is a broad minimum in the observed curve starting at about $115 \text{ GeV}/c^2$. The expectation for signal plus background hypothesis crosses the observed curve close to this value,

indicating that a Higgs boson with such mass is more favoured than the “*b*” hypothesis, albeit at low significance. Studies of the contributions from individual experiments and final-state topologies have shown that this signal-like behaviour mainly originates from the ALEPH data in the four-jet channel. Figure 1.b shows the confidence level $1 - CL_b$ for test masses in the range $80\text{--}120 \text{ GeV}/c^2$. In the region $m_H \sim 98 \text{ GeV}/c^2$ the deviation from the background only hypothesis corresponds to 2.3 standard deviations. In the region of m_H above $115 \text{ GeV}/c^2$ it corresponds to 1.7 standard deviations. This deviation, though of low significance is compatible with a SM Higgs boson signal, while being also in agreement with the background hypothesis. A 95% confidence level lower limit on the Higgs mass may be set by identifying the mass region where $CL_s < 0.05$: the median limit expected in the absence of a signal is $115.3 \text{ GeV}/c^2$ and the observed limit is $114.4 \text{ GeV}/c^2$.

3 Bounds for the Higgs boson coupling

The combined LEP data are also used to set 95% confidence level upper bounds on the HZZ coupling in non-standard models². The limits are expressed in terms of ξ^2 defined as the ratio of the non-standard HZZ coupling and the same coupling in the SM. In deriving these limits LEP1 data collected at the Z resonance have been combined with LEP2 data between 161 and 209 GeV. This limit is valid only in the hypothesis that the Higgs boson has SM branching ratios, but extensions of the SM could easily predict suppressed couplings to b-quarks, therefore flavour independent searches have been performed by the four LEP collaborations, analysing the four jet ($q\bar{q}q\bar{q}$), missing energy ($q\bar{q}\nu^+\nu^-$) and leptonic ($q\bar{q}l^+l^-$) topologies. Data collected for $189 \leq \sqrt{s} \leq 209 \text{ GeV}$ have been analysed without finding any evidence of the presence of a signal³. The coupling limits obtained by the individual experiments are not far from the ones provided by the usual SM searches, searching for final states containing b-quarks. The observed (median expected) limits on the Higgs mass assuming SM production cross-sections are 110.6 (110.5) GeV, 110.6 (108.0) GeV, 108.7 (110.3) GeV and 109.2 (108.0) GeV for ALEPH, DELPHI, L3 and OPAL, respectively. A LEP combination of the results is expected soon.

4 Two Higgs Doublet Models

It is important to study extensions of the SM containing more than one physical Higgs boson in the spectrum: in particular Two Higgs Doublet Models (2HDMs) which are attractive since they add new phenomena with the fewest new parameters and since the MSSM is a special case of 2HDM in which the addition of supersymmetry adds new particles and constrains the model itself. In the context of general 2HDMs the Higgs sector comprises five physical Higgs bosons: two neutral CP-even scalars, h^0 and H^0 (with $m_h < m_H$), one CP-odd scalar, A^0 , and two charged scalars, H^\pm . At the centre-of-mass energies accessed by LEP, the h^0 and A^0 bosons are expected to be produced predominantly via two processes: the *Higgs-strahlung* process, $e^+e^- \rightarrow h^0Z^0$, and the *pair-production* process, $e^+e^- \rightarrow h^0A^0$. The cross-sections for these two processes, σ_{hZ} and σ_{hA} , are related at tree-level to the SM cross-sections by the following relations:

$$\sigma_{hZ} = \sin^2(\beta - \alpha) \sigma_{HZ}^{\text{SM}}, \quad \sigma_{hA} = \cos^2(\beta - \alpha) \bar{\lambda} \sigma_{HZ}^{\text{SM}}, \quad (1)$$

where σ_{HZ}^{SM} is the *Higgs-strahlung* cross-section for the SM process $e^+e^- \rightarrow H^0Z^0$, and $\bar{\lambda}$ is a phase-space factor.

Within 2HDMs the choice of the couplings between the Higgs bosons and the fermions determines the type of the model considered. In the Type II model the first Higgs doublet (ϕ_1) couples only to down-type fermions and the second Higgs doublet (ϕ_2) couples only to up-type fermions. In the Type I model the quarks and leptons do not couple to the first Higgs doublet (ϕ_1), but couple to the second Higgs doublet (ϕ_2).

OPAL PRELIMINARY

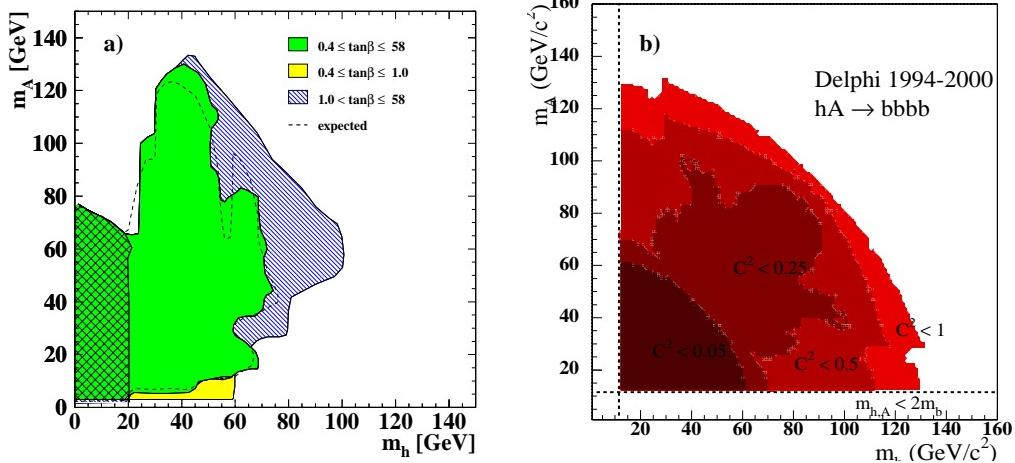


Figure 2: Figure 2: a) Excluded (m_A, m_h) region independent of α (solid line) and expected exclusion (dashed line). Different $\tan\beta$ intervals have been considered. The cross-hatched region is excluded using Γ_Z constrains only. b) Excluded c^2 contours in the (m_A, m_h) plane assuming that h^0 and A^0 decay to $b\bar{b}$ in 100% of the cases.

The Higgs sector in the MSSM is a 2HDM(II).

In a 2HDM the production cross-sections and Higgs boson decay branching ratios are predicted for a given set of model parameters. The coefficients $\sin^2(\beta - \alpha)$ and $\cos^2(\beta - \alpha)$ which appear in Eq. (1) determine the production cross-sections. The decay branching ratios to the various final states are also determined by α and β . In the 2HDM(II) the tree-level couplings of the h^0 and A^0 bosons to the up- and down-type quarks relative to the canonical SM values are:

$$h^0 c\bar{c} = \cos\alpha/\sin\beta, \quad h^0 b\bar{b} = -\sin\alpha/\cos\beta, \quad A^0 c\bar{c} = \cot\beta, \quad A^0 b\bar{b} = \tan\beta. \quad (2)$$

From these equations it is easy to see that in wide portions of the parameter space the couplings to b-quarks are not the dominant ones.

The OPAL collaboration has performed a detailed scan over broad ranges of these parameters⁴: $1 \leq m_h \leq 100$ GeV, $5 \leq m_A \leq 2$ TeV, $0.4 \leq \tan\beta \leq 58.0$ and $\alpha = 0, -\pi/8, -\pi/4, -3\pi/8$ and $-\pi/2$. All available neutral Higgs searches for centre-of-mass energies $189 \leq \sqrt{s} \leq 209$ GeV have been combined with LEP1 data collected at the Z peak. Both analyses making use of b-tagging and flavour independent searches have been used. The most general exclusion obtained by OPAL is shown in Figure 2.a. The DELPHI collaboration has also produced limits in the (m_A, m_h) plane on c^2 , defined as the ratio of the 2HDM production cross-section for the process $e^+e^- \rightarrow h^0 A^0$ and the maximal production cross-section⁵. These limits are obtained with the assumption of 100% decays into the following specific final states: $h^0 A^0 \rightarrow b\bar{b} b\bar{b}$, $h^0 A^0 \rightarrow A^0 A^0 A^0 \rightarrow b\bar{b} b\bar{b} b\bar{b}$, $h^0 Z^0 \rightarrow A^0 A^0 Z^0 \rightarrow b\bar{b} b\bar{b} q\bar{q}$, the excluded contours for the $h^0 A^0 \rightarrow b\bar{b} b\bar{b}$ case are shown in Figure 2.b.

4.1 MSSM Higgs searches

The MSSM is a 2HDM(II) in which supersymmetry adds new particles and constrains the model. The production cross-sections and decay branching ratios depend not only on the masses but also on the values of α and β as in equations 1 and 2. In most of the parameter space the decays of h^0 and A^0 into $b\bar{b}$ and $\tau^+\tau^-$ dominate, therefore the searches for MSSM signatures concentrate on these final states, but for the values of parameters for which these decays are suppressed also flavour-independent searches are taken into account. The individual searches of the four LEP collaborations for the processes $e^+e^- \rightarrow h^0 Z^0$ and $e^+e^- \rightarrow h^0 A^0$ which include the data taken at $88 \leq \sqrt{s} \leq 209$ GeV, have been combined as described in⁶. No evidence for the presence of

a signal has been discovered. Exclusion limits have been obtained in three ‘benchmark’ MSSM parameter scans. The first benchmark corresponds to *no-mixing* in the scalar-top sector; a second to large mixing and the parameters tuned to maximise the parameter space along m_h (m_h -*max* hereafter); a third scan (*large- μ* hereafter) is designed to highlight choices of MSSM parameters for which the h^0 does not decay into $b\bar{b}$ due to large loop corrections.

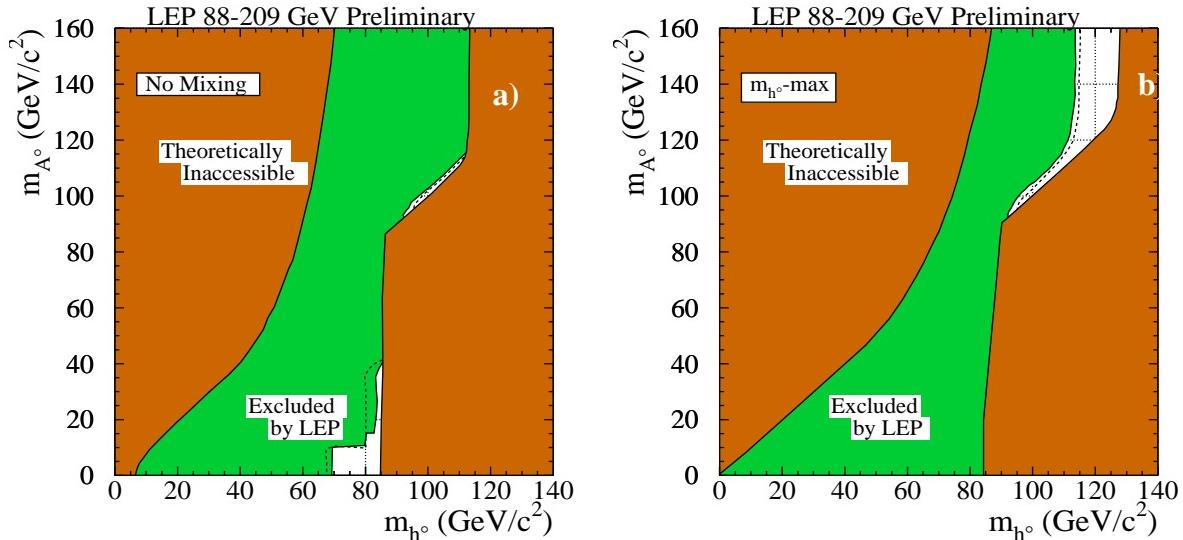


Figure 3: The MSSM exclusion (a) for the no-mixing scenario and (b) for the m_h -*max* scenario. The figures show the excluded and the theoretically not allowed regions as a function of the Higgs boson mass.

Figures 3.a) and 3.b) show the excluded regions in the *no-mixing* and in the m_h -*max* scenarios. The *no-mixing* scenario is almost completely excluded except for the small region for low values of m_A and $m_h \geq 60$ GeV. In the final forthcoming LEP combination, the unexcluded area will be considerably reduced: the region for $2 \leq m_A \leq 10$ GeV/ c^2 is already excluded by a new search by OPAL for a low mass A in the $e^+e^- \rightarrow h^0 Z^0 \rightarrow A^0 A^0 Z^0$ process⁷, which is dominant in this mass range. The region for $m_A \geq 12$ and $m_h \geq 80$ GeV has been excluded by the latest MSSM scan performed by the DELPHI collaboration⁸. The *large- μ* scenario has been completely excluded at 95% CL by using the flavour independent searches.

4.2 CP violating MSSM Higgs searches

The introduction of CP violating phases into the MSSM is theoretically appealing, since CP violation is one of the three requirements to be fulfilled to generate the cosmic matter/antimatter asymmetry. CP violating phases in the sector of direct soft supersymmetry breaking lead to an introduction of CP violation to the MSSM Higgs sector via first order loop corrections from third generation squarks to the otherwise CP invariant Higgs potential. This would allow the MSSM to fulfil the requirements for generating the cosmic baryon asymmetry.

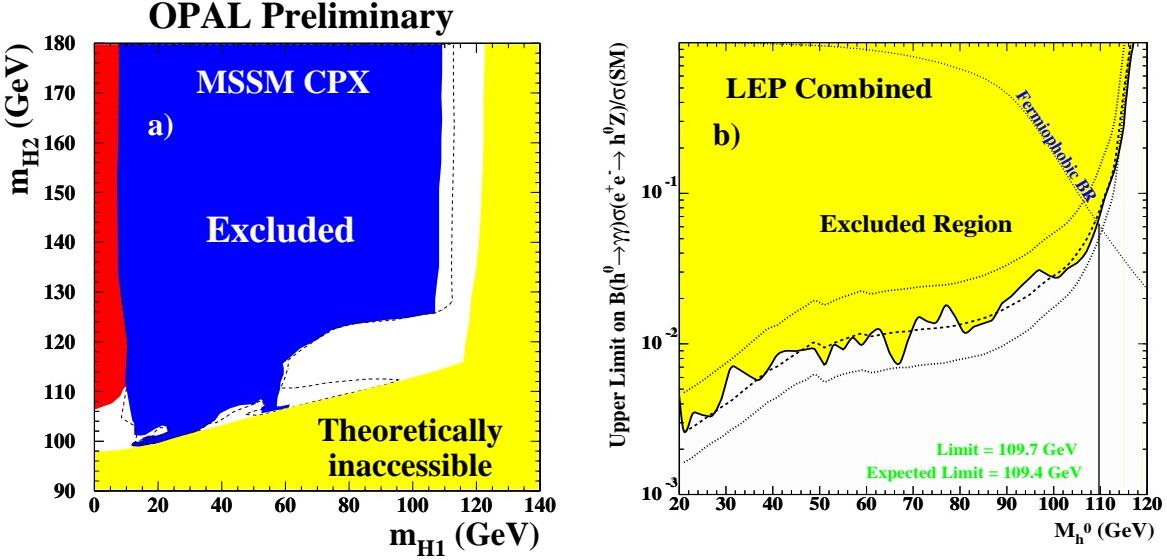


Figure 4: a) 95% CL excluded areas in the CP violating MSSM scenario. The observed excluded region is shown in the (m_{H_1}, m_{H_2}) . The expected excluded region is indicated by the dashed line and the theoretically inaccessible region is light shaded. b) Combined LEP experimental limits for Higgs bosons decaying into di-photons. The 95% CL confidence level upper limit on the $B(h^0 \rightarrow \gamma\gamma) \times \sigma(e^+e^- \rightarrow h^0 Z^0)/\sigma(\text{SM})$ is shown as a function of the Higgs mass. Also shown (dotted line) is the branching fraction obtained for the benchmark fermiophobic model. The median expected limits and the $\pm 2\sigma$ confidence level region are denoted by the dashed curves. The combined limit is indicated by the vertical line.

In a CP violating MSSM scenario, the Higgs production mechanisms proceed as in a CP conserving MSSM. As the Higgs mass eigenstates do not have defined CP quantum numbers, the production of all three mass eigenstates in *Higgs-strahlung* is allowed and the coupling of the Higgs bosons to the Z^0 is modified. For some choices of the parameters, H_1 , decouples completely from the Z^0 , while the production of the second lightest Higgs, H_2 , also has small or vanishing cross-section, allowing for more complex experimental situations and reducing the accessible parameter regions. In large parts of the parameter space the production of both H_1 and H_2 in *Higgs-strahlung* is possible. The production of the heaviest Higgs state, H_3 , has no relevant cross-section at LEP energies in all production channels for the scenario under study. The OPAL collaboration has reinterpreted all the searches for neutral Higgs bosons performed for $88 \leq \sqrt{s} \leq 91$ GeV in this context to constrain the parameter space of CP violating MSSM scenarios⁹. The choices of the parameters used for the benchmark scans are fulfilling the electric dipole moment (EDM) constraints and maximise the CP violating effects. The results of the scans are shown in Figure 4

5 Charged Higgs

Charged Higgs bosons are predicted by 2HDM's. The present searches for charged Higgs bosons are placed in the general context of 2HDM's where the mass is not constrained, since in the MSSM at tree-level the H^\pm is constrained to be heavier than the W^\pm bosons and only for extreme choices of the parameters loop corrections can drive the mass to lower values. At LEP2 energies charged Higgs bosons are expected to be produced mainly through the process $e^+e^- \rightarrow H^+H^-$. In the 2HDM at tree level the production cross-section is fully determined by m_{H^\pm} ;

5.1 Search for the $H^+ \rightarrow c\bar{s}$ and $H^+ \rightarrow \tau^+\nu$ decays

The LEP collaborations have searched for charged Higgs bosons under the assumption that the two decays $H^+ \rightarrow c\bar{s}$ and $H^+ \rightarrow \tau^+\nu$ exhaust the H^+ decay width¹⁰; however, the relative branching ratio is not predicted. Thus, the searches encompass the following H^+H^- final states: $(c\bar{s})(\bar{c}s)$, $(\tau^+\nu)(\tau^-\bar{\nu})$ and the mixed mode $(c\bar{s})(\tau^-\bar{\nu}) + (\bar{c}s)(\tau^+\nu)$. The combined search results are presented as a function of the branching ratio $B(H^+ \rightarrow \tau^+\nu)$. As a preliminary results the L3 collaboration observes a 2.7σ deviation from the background behaviour for $m_{H^\pm} \simeq 68$ GeV/ c^2 , which has not been confirmed by the other collaborations. This effect is under investigation. The 95% CL observed (expected) lower limits on the charged Higgs boson mass for any value of $B(H^+ \rightarrow \tau^+\nu)$ obtained by the other LEP experiments are: 79.3 (77.1) GeV/ c^2 for ALEPH, 74.3 (76.4) GeV/ c^2 for DELPHI, 75.5 (74.5) GeV/ c^2 for OPAL. The final LEP combination is expected soon.

5.2 Search for the $H^+ \rightarrow A^0W^{+*}$ decays

The OPAL and DELPHI collaborations have also searched for the process $e^+e^- \rightarrow H^+H^- \rightarrow A^0W^{+*}A^0W^{*-}$, which is relevant at low $\tan\beta$ in 2HDM(II) and dominant for $\tan\beta \leq 1$ in 2HDM(I), if kinematically allowed¹¹. These searches are restricted to values of m_A larger than 12 GeV/ c^2 , since the A^0 is assumed to decay into $b\bar{b}$ final states, while leptonic and hadronic decays of the the W are considered.

5.3 Search for doubly charged Higgs

Doubly charged Higgs bosons appear in theories beyond the Standard Model, like in left-right symmetric models. In such models the $SU(2)_R$ symmetry is broken by triplet Higgs fields which don't conserve baryon and lepton numbers. The DELPHI and OPAL collaborations have recently searched for pair-produced doubly charged Higgs bosons. Both collaborations look for $H^{++} \rightarrow \tau^+\tau^+$ decays while OPAL also searches for $H^+ \rightarrow \mu^+\mu^+$, e^+, e^- decays¹². The data analysed have been taken at $189 \leq \sqrt{s} \leq 209$ GeV. A 95% CL limit on the charged Higgs boson mass of 97.3 GeV/ c^2 for any value of the $h_{\tau\tau}$ Yukawa coupling has been obtained by DELPHI, while OPAL extracts a lower limit of 98.5 GeV/ c^2 for Higgs bosons decaying in 100% of the cases to two leptons of the same sign with 100% branching ratio.

6 Fermiophobic Higgs

In the minimal Standard Model, the rate of Higgs boson decays into photons is too small for observation at existing accelerators, but in other theoretical models, like the 2HDM(I) for certain values of the parameters the h^0 couples only to bosons. The class of “fermiophobic” Higgs models includes the more general “Bosonic” Higgs model, and Higgs-Triplet models where the particles formed from the triplet fields are fermiophobic. For $m_h < 80$ GeV, the fermiophobic Higgs decays primarily into $\gamma\gamma$, while for higher masses decays into WW^* and Z^0Z^{0*} can be observed. The four LEP experiments search for events having two energetic, isolated photons using data taken at $189 \leq \sqrt{s} \leq 209$ GeV. In addition, the Z^0 decay products are either classified, or, in the case of $Z^0 \rightarrow \nu^+\nu^-$, acoplanarity on the photons is required. For the 2000 data, the ALEPH analysis is “global” (the final states are not listed separately). The combination of the LEP data data collected between 88 and 209 GeV in the centre-of-mass result in an upper limit on the on the branching ratio $B(h^0 \rightarrow \gamma\gamma)$ as a function of the Higgs mass¹³: an observed (expected) lower limit on the Higgs boson mass of 109.7 (109.4) GeV/ c^2 as can be seen in Figure 4.

7 Decay mode independent searches

Searches for neutral scalar bosons S^0 produced in association with the Z^0 have been developed by OPAL in order to search for Higgs bosons with a minimum dependence on model assumptions¹⁴. The analyses are based on studies of the recoil mass spectrum of $Z^0 \rightarrow e^+e^-$ and $\mu^+\mu^-$ events and on a search for S^0Z^0 events with $S^0 \rightarrow e^+e^-$ or photons and $Z^0 \rightarrow \nu^+\nu^-$. The limits are sensitive to decays of the S^0 into hadrons, leptons, photons, invisible particles or if the S^0 lifetime is long enough to escape detection. The analyses use the full luminosity collected at the Z^0 peak at LEP1 and 662.4 pb^{-1} of LEP2 data collected at $183 \leq \sqrt{s} \leq 209 \text{ GeV}$. The results are presented in terms of limits on the scaling factor k given by the ratio of the *Higgs-strahlung* production cross-section in a given model and the SM cross-section. Values for $k \geq 0.1$ are excluded for $m_S \leq 19 \text{ GeV}/c^2$ and an observed (expected) lower limit on m_S of 81 (64) GeV/c^2 is obtained when assuming SM production cross-section.

8 Conclusions

Neutral and charged Higgs bosons have been searched by the LEP collaborations in any existing and theoretically appealing model that predicts the existence of Higgs bosons detectable at LEP. Both when searching for specific models or when using the model independent approaches, no evidence of a signal has been found and exclusion limits on the parameter space of the different models have been extracted.

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